

## **Active Turbulence Following Using an AUV**

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### **LONG-TERM GOALS**

The long-term goal is to be able to follow any turbulence structure in the ocean environment with an autonomous underwater Vehicle (AUV) while quantifying, in real time, the turbulence field.

### **OBJECTIVES**

Scientific or Technological Objectives of this effort are to make direct *in-situ* measurements of the turbulence levels (i) in the wake of a self-propelled underwater vehicle, (ii) in the wake of a surface vehicle and (iii) to program an AUV to actively follow a turbulent wake or event.

### **APPROACH**

With the final objective of following a turbulent event, including the wake from a marine vehicle in the ocean using an AUV, three tasks are identified: First, quantify the characteristics of the turbulent wake. Second, develop a controller to follow the turbulent wake. Third, demonstrate the resulting controller in the ocean environment by following an actual wake.

The first task of quantifying the turbulent wake will be achieved through the following process:

- Measure the turbulent wake behind a ship and an underwater vehicle to quantitatively map the parameters that make it unique from ambient turbulence.
- Compare the measurements obtained in the first step to previous experimental work by others for validation of the methods used.
- Compare the measurements obtained in the first step and obtained by others to analytic models developed by others.
- Identify or develop the analytic model to be used as a basis for the design of the controller.

The result of this first task will be an understanding of the physical process that the controller must identify and follow.

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The second task, to develop a controller to follow the turbulent wake, can also be considered a process as follows:

- Define a turbulent wake as being unique from ambient turbulence in the water column.
- Determine the controller requirements based on the results from the first task and the capabilities of the turbulence measurement system.
- Design a controller that will transparently integrate with the AUV control software.

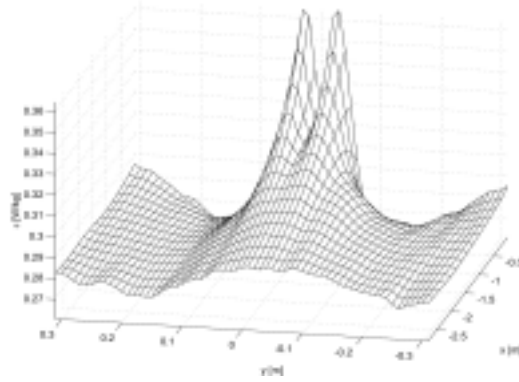
The ocean measurements of the vehicle wake will unavoidably include the ambient turbulence. In the absence of ambient turbulence, the limitation on resolution of the wake will be the internal noise floor of the data acquisition system, currently at a measured dissipation rate of  $10^{-9}$  and the noise floor of the sensor, which is of a similar magnitude [1]. Near the surface, ambient turbulence levels can be expected to range from  $5 \times 10^{-5}$  for very active atmospheric forcing to  $10^{-6}$  or less for the moderate conditions chosen for the experiment [2].

The estimation of the turbulent dissipation in the time domain takes on the following form. For implementation as a control signal to the vehicle controller to optimize, the dissipation rate is normalized to a range of 0 to 255. The ambient turbulence level is estimated during the mission and is removed as well. This results in the following equation for the real time estimation of the dissipation rate:

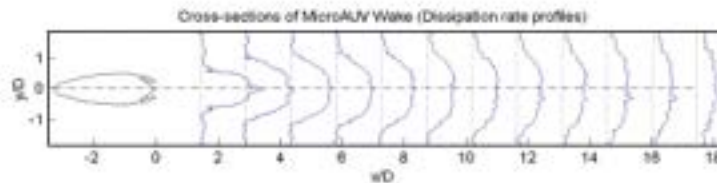
$$\varepsilon = \frac{15\nu}{U^2} \left[ \frac{dw}{dt} \right]^2; \varepsilon_{[0-255]} = \frac{255}{\log(\varepsilon_{\max}) - \log(\varepsilon_{\min})} \left( \log \left[ 7.5\nu \frac{1}{U^2} \left( \frac{1}{\frac{\rho}{\rho_{\text{fresh water}}} C_Y K} \right)^2 \frac{1}{N} \sum_{i=1}^N V_i^2 \right] - \log(\varepsilon_{\min}) \right)$$

## WORK COMPLETED

The work completed includes a numerical time simulation of the wake following controller, laboratory measurements of the wake of an AUV, in-situ open ocean measurements of the wake of a ship and in-situ open ocean measurements of the wake of an AUV. Detailed laboratory measurements of the zero-momentum wake of an AUV have also been conducted with mappings of the mean velocity field as shown in Figure 2 and the turbulent dissipation as shown in Figure 3.

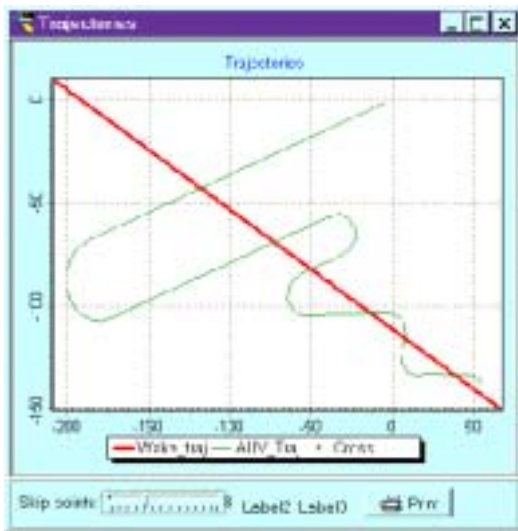


**Figure 2. The mean velocity field in the zero-momentum wake behind a propeller driven AUV.**



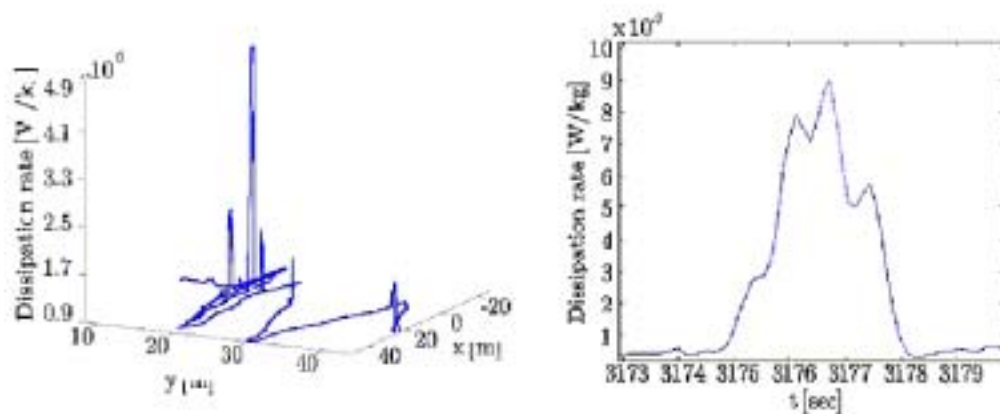
**Figure 3. The measured dissipation rate in the zero-momentum wake behind an AUV.**

In order to test the proposed controller, a time domain simulation was created and used to refine the control strategy for wake following. In Figure 4a, the path of the target AUV is shown in red while that of the following AUV is shown in green. The following AUV begins with a lawn-mower survey pattern and upon detecting the wake at the first crossing, turns back and crosses the wake a second time to establish the direction of the wake vector. The following vehicle can then begin a local optimization of the wake and follow the lead vehicle while optimizing the turbulence signal.

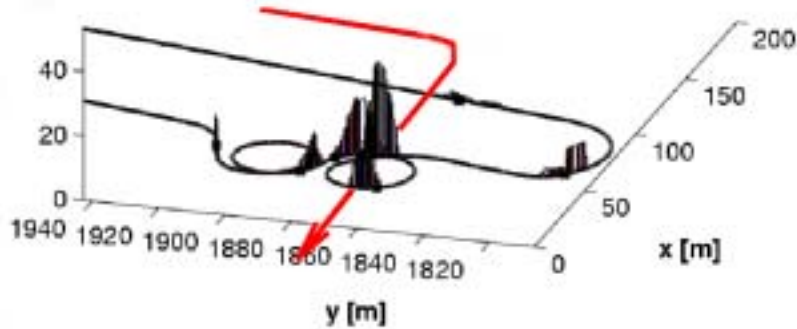


**Figure 4. Simulation of the wake following controller (left). The path of the lead vehicle is shown in red and the following vehicle in green. Note the user interface and the wake following optimization. Deployment of the Ocean Explorer (OEX) AUV with the turbulence package.**

In addition to laboratory measurements, in-situ open ocean measurements have been made in the wakes of both a surface vessel (RV Oceaneer) and an AUV (OEX) shown in Figure 4b. The results from one of five experiments are shown. In this experiment, there was a lead AUV which followed a straight path and a following AUV which trailed the lead crossing the wake of the lead vehicle multiple times. The actual paths in a coordinate system relative to the lead vehicle is shown in Figure 5 with the dissipation rate shown in the vertical scale and a detail of one of the crossings. With the expected shape of the dissipation field known, a controller was designed and tested in the wake of a surface ship. The wake following controller is integrated into the software architecture of the OEX controller. The real time dissipation rate is estimated from the measurements of the two shear probes in the turbulence package implementing an adaptive strategy to reemove the ambient turbulence levels. The rate is scaled to a single byte value (0-255) with the average background ambient turbulence estimated and removed in real time. The information is then sent via ethernet to the vehicle controller. The modular controller architecture of the OEX allows a wake following module to control the path of the vehicle. For this experiment, only the horizontal plane is considered. The controller was tested by programming the vehicle to go in a straight path to aquire the background levels and then begin a lawnmower search pattern with a 180° turn to the right. The RV Oceaneer followed about 80 meters behind the AUV and made a 90° turn to the right when the AUV was observed to begin the search pattern. The AUV then crossed the wake of the boat, detected the wake and began to turn back and follow the wake. Due to the nonlinear response of the shear probes, the boat wave wake created a false signal, confused the controller and caused the vehical to respond eratically as shown in Figure 6. This problem will not be encountered if the wake were generated by an underwater vehicle since the vehicle would not be so close to the surface (<1meter).



**Figure 5. Measured dissipation in the wake of an AUV by an AUV with the turbulence package. The x and y coordinates are relative to the lead vehicle. Detail (right) of a single crossing of the wake of an AUV with the resulting estimated dissipation rate.**



**Figure 6.** *At sea demonstration of the wake following controller in the wake of a surface vessal. The value of the dissipation as sent to the controller is shown in the vertical scale.*

## RESULTS

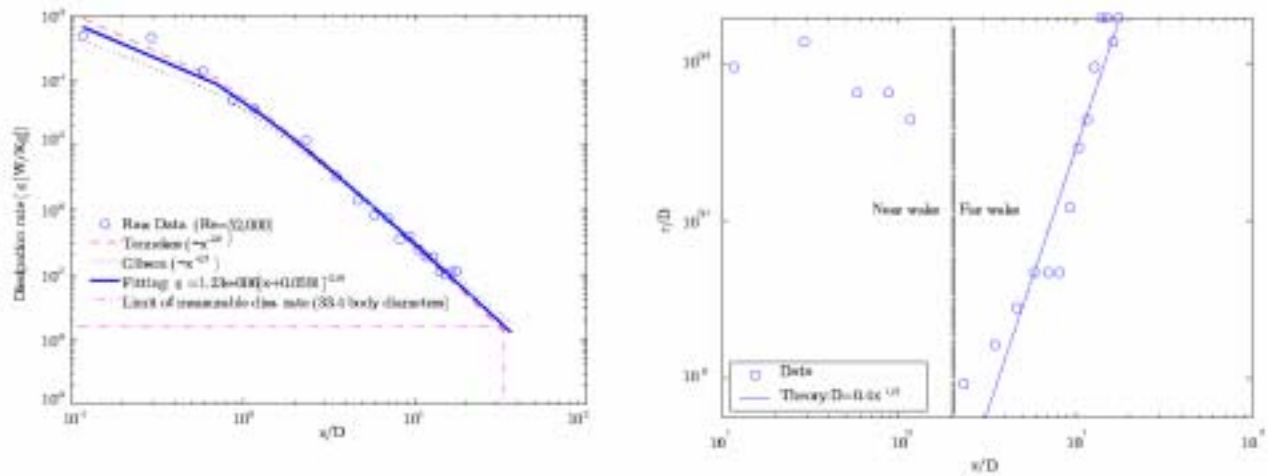
The theoretical expectations agree well with the laboratory measurements both for the expected levels of turbulent dissipation and for the spreading of the wake. Figure 7a shows the laboratory measurements plotted together with the model given by Tennekes [6] and by Gibson [7] for the dissipation rate in the wake of a self-propelled vehicle and a sphere. In Figure 7b, The spreading from the experiments is compared with the theoretical prediction with excellent agreement as well. With a clear understanding of the expected form of the wake, a controller was designed and tested with perhaps not perfect results, but none the less encouraging. The real time turbulent dissipation levels were accurately measured with the ambient turbulence levels removed. The controller was successfully integrated into the control architecture of the OEX AUV. And the controller did respond to a real wake in the open ocean. The results from this experiment revealed some of the difficulties in using non-linear sensors for detection with contamination from wave orbitals. These difficulties should be of a much lower magnitude for detection and following the wake of an underwater vehicle with the operations being away from the surface and gravity wave effects. At sea measurements of the wake from an AUV In fact prove this out.

## IMPACT/APPLICATIONS

This work demonstrated the adaptive capabilities of AUVs for wake following. The turbulence package developed at Florida Atlantic University has proven to be robust and flexible in this advanced application by estimating, in real-time, the dissipation rate. Security applications for clandestine harbor surveillance with the capability to resolve and follow a wake are many and it is hoped that this work will result in a safer environment for our nations commerce.

## TRANSITIONS

Transition of this work is occurring in the form of a proposed joint project with the bioluminescence research of Edith Widder at Harbor Branch Oceanographic Institute. Additionally, efforts are ongoing to publish these results and make the knowledge available to the wider oceanographic community.



**Figure 7. a) Comparison of experimental data with models for the decay of turbulence in a wake. b) Comparison of experimental data with a model for the spreading of a wake in the near and far regions.**

## RELATED PROJECTS

The PI has recently begun an SBIR (N01-033) to develop a small surface flux buoy. The fluxes will be estimated using the eddy correlation method and will utilize the experience gained from this project in turbulence measurement.

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## **PUBLICATIONS**

*Direct In-Situ Measurement of the Wake of a Self-Propelled Vehicle*. Y.G. LePage, K.W. Holappa and M.R. Dhanak. Submitted to the *Journal of Ship Research*. June, 2001.